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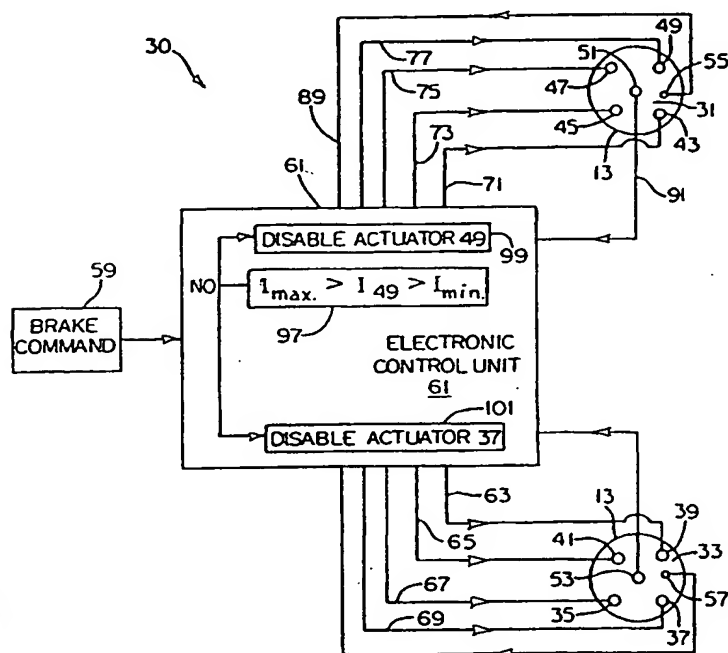
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(54) Title: ELECTRICALLY ACTUATED BRAKE WITH VIBRATION DAMPING



(57) Abstract: An electrically actuated braking system (30) of the type having a plurality of brake actuators (35, 37, 39, 41, 43, 45, 47, 49) disposed on a carrier housing (13) to selectively apply a braking force to effect the restraint of wheel rotation has the particular actuators employed during a braking event determined, at least in part, by monitored wheel motion. The system (30) reduces brake energy consumption and heat generation during slow speed operations, reduces braking induced vibration, and compensates for individual actuator failure. The system (30) includes a first circuit for energizing only a first proper subset of the plurality of the brake actuators (35, 37, 39, 41, 43, 45, 47, 49) upon occurrence of a braking command (59); a second circuit for energizing only a second proper subset of the plurality of brake actuators upon occurrence of a braking command; and wheel motion monitors (51, 53) providing control signals for selectively enabling the first circuit and not the second circuit in response to certain of the control signals, the second circuit and not the first circuit in response to other of the control signals, and both the first and second circuits in response to still other of the control signals. Typically, there are four disjoint

proper subsets the union of which comprises all actuators for the given brake. Preferably the first and second circuits each energize exactly one brake actuator. In one form, the first and second circuits are both energized during normal braking while the first, but not the second, is energized during slow speed taxi or towing operation. In another form, the first subset comprises all properly operating brake actuators while the second comprises all malfunctioning brake actuators and the second circuit remains un-energized.



*For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.*

ELECTRICALLY ACTUATED BRAKE WITH VIBRATION DAMPING  
BRIEF SUMMARY OF THE INVENTION

The present invention relates generally to methods and apparatus for braking vehicles and more especially to such methods and apparatus for the selective control of electrically actuated aircraft braking systems.

An illustrative electrically actuated aircraft braking system is shown in U.S. Patent 4,865,162 which teaches a plurality of annularly disposed electrically energizable torque motor and roller screw drive mechanisms for selectively engaging a pressure plate of a wheel and brake assembly and compressing a disc brake stack to retard aircraft motion. In such electrically actuated braking systems, all electromechanical actuators associated with a given wheel are actuated each time the brakes for that wheel are applied. This can result in undesirable heating of the brake assembly and sometimes unnecessary wear of the brake disks. Moreover, failure of one or more electromechanical actuators can result in uneven braking and a tendency for the aircraft to "pull" away from the side on which the failure has occurred due to a now lesser braking force on that side. Finally, most braking systems sometimes experience a "chatter" or undesirable vibration during a braking event.

The problem of disk wear is addressed in U.S. Patent 4,923,056 where it is suggested to energize less than all of the brake assemblies during braking associated with slower speed taxi or towed situations where lesser braking force is required. While this patented system may alleviate the disk wear problem, all electromechanical actuators associated with a given wheel are actuated each time the brakes for that wheel are applied leaving the problems of undesirable heating of the brake assembly, vibration and uneven braking unresolved.

It is desirable to provide a braking system which reduces brake induced vibration, undesired unbalanced braking force, and unnecessary brake assembly heating all at a very modest increase in braking system cost.

The present invention provides solutions to the above problems by providing individual electromechanical actuator control within a brake system. Active vibration damping is a benefit of this system design and architecture, as are enhanced fault accommodation, improved thermal management and improved park and tow capabilities.

In accordance with one form the invention, a braking system of the type having a plurality of individual actuators selectively energizable upon a braking command to frictionally restrain rotation of a vehicle wheel includes a control circuit operable in a normal braking mode to equally or  
10 unequally energize all of the plurality of actuators upon receipt of a braking command, and in a second mode to equally or unequally energize less than all of the plurality of actuators associated with a given wheel upon receipt of a braking command. The second mode may be a taxi mode where less than all actuators (a proper subset of all actuators for  
15 that brake) are enabled to diminish heat generation and energy consumption, a mode where the actuators are enabled in a routine to reduce brake vibration, or a failed actuator mode where a failed actuator and a matching actuator on the opposite side of the vehicle are disabled to maintain equal left-right retarding forces on the vehicle. An alternative  
20 failed actuator mode involves increasing the level of energization to the remaining actuators associated with the wheel of the failed actuator.

#### BRIEF DESCRIPTION OF THE DRAWING

Figure 1 is a cross-sectional view of a portion of a prior art vehicle wheel and brake assembly showing one electromechanical actuator;

25 Figure 2 is a schematic illustration of the electrically actuated brake system of the present invention showing illustrative left and right wheel brake assemblies with eight electromechanical brake actuators; and

Figure 3 is a schematic illustration of the operation of the electrically actuated brake system of Figure 2.

30 Corresponding reference characters indicate corresponding parts throughout the several views of the drawing.

### DESCRIPTION OF THE PREFERRED EMBODIMENT

In the wheel and brake assembly of Figure 1, an illustrative electromechanical actuator 11 of brake carrier housing 13 is fixed to torque tube 14 by bolts 15. A wheel 17 is journaled for rotation about the axle 19. A brake disk stack has alternate rotor disks such as 21 and 23 fixed to and rotatable with the wheel 17 while intervening stator disks such as 25 and 27 are stationary and fixed to torque tube 14 connected with brake carrier housing 13. When actuator 11 (along with a plurality of similar annularly disposed actuators) is energized, piston 12 extends forcing the brake pressure plate disk 29 to compress the disk stack and slowing the vehicle as is conventional in multi-disk brake assemblies.

In Figure 2, an electrically actuated braking system 30 comprises two wheel and brake assemblies 33 and 31 that are illustrated schematically with each having four electromechanical actuators ("EMAs") 35, 37, 39, 41, 43, 45, 47 and 49 mounted on the respective brake carrier housings 13 in an annular pattern about the axis of wheel rotation. EMAs may be obtained from companies such as MPC Products Corporation, Skokie, IL and AlliedSignal Aerospace, Torrance, CA . The actuators or EMAs are selectively energizable upon occurrence of a braking command to apply a braking force to a pressure plate thereby compressing a brake disk stack and restraining wheel rotation. Each wheel and brake assembly 31, 33 also supports a wheel speed or torque sensor 51 and 53 as well as a vibration sensor 55 and 57. Except for the presence of the vibration sensors 55 and 57, the two wheel and brake assemblies 31 and 33 of Figure 2 may, for example, be of the conventional type as described in Figure 1.

When the pilot or other vehicle operator initiates a commanded braking event, the command, illustrated at 59, is supplied to an electronic control unit (ECU) 61 which normally supplies an enabling current to each electromechanical actuator ("EMA") by way of circuits 63, 65, 67, 69,

71, 73, 75 and 77. Proper operation of each actuator is monitored during a braking event. This may be accomplished by locating individual motion transducers at the EMA locations. It may also be achieved by monitoring actuator current flow as illustrated for one actuator 49 at 97. So long as the current is not excessive or too low, the actuator 49 remains enabled during braking. Should an indication that the current is not within limits occur, the actuator 49 is disabled as at 99. Most drivers have at one time or another experienced the sideways force or "pull" caused when one wheel is braked to a greater extent than another. Disabling actuator 49 could induce such a "pull." When the control unit 61 disables a single, failed EMA, to maintain balance between brakes, it may also disable a properly functioning EMA such as 37 on the other brake assembly as shown at 101. This would reduce the number of EMAs generating brake actuation force to 75% of the baseline which is consistent with a relatively crude brake control system. Disabling an actuator upon the occurrence of improper operation reduces the braking force on the associated wheel, and compensating by disabling another actuator of another wheel to reduce the braking force on the another wheel to substantially the same reduced level as the associated wheel restores the balance. For simplicity, only one actuator 49 is shown in Figure 2 as being monitored and only the pair of actuators 37 and 49 shown with disabling circuits. It will be understood that the electronic control unit 61 would typically include current monitoring circuits and disconnect circuits for each EMA.

Techniques for monitoring actuator behavior, such as by locating individual motion transducers at the actuator locations and corrective techniques are indicated generally at 93 and 95 in Figure 3. The corrective action 95 for maintaining left and right braking balance may be achieved by inhibiting a failed EMA and compensating for any potential imbalance by driving the other three EMA's on the same wheel harder. The drive to the four EMA's on the other brake would be unchanged.



With this system, the number of actuators is reduced and the level of actuator energization to at least some of the reduced number of actuators is increased thereby avoiding the tendency of another more forcefully braked wheel inducing a sideways force on the vehicle.

5 In Figure 3, speed and vibration monitoring for a single brake are also illustrated. The speed or torque sensor 51 of brake 31 is coupled by circuit 91 to the electronic control unit 61. The vibration sensor 55 (which may, for example, be an accelerometer) of brake 31 is coupled to the electronic control unit 61 by circuit 89. Clearly, such monitoring may  
10 be duplicated for any other or all brakes as desired. The ability to remove power from individual EMA's and their associated power control electronics allows selective operation during periods where thermal management is a concern. One such condition is during long periods of aircraft taxi. The benefit of independent control is the ability to remove  
15 power (a significant source of heat during these conditions) from the EMA's and power control electronics in order to allow cooling. Under parking, and towing conditions, lower power consumption is achieved by enabling only the number of actuators required. If only one EMA is required to generate the desired level of brake application, there is no  
20 need to power two EMA's and additional power control electronics (as would be the case with paired EMA control). Since parking and towing operations are commonly associated with "no aircraft power" conditions (i.e. battery power, not engine generated), there is an advantage to this "only as required" operation. When the vehicle operator issues a  
25 braking command at 59, normal braking commences as indicated at 81. The control unit 61 may monitor the aircraft speed as indicated at 79 and operate all the brake actuators in one mode (normal braking 81) during landing and roll-out of the aircraft so long as the speed exceeds a predetermined value and switch to a second mode 83 where certain  
30 actuators are disabled or the actuator drive reduced during taxi and towing of the aircraft when the speed drops below that predetermined

minimum. Speed or torque sensor 51 may also participate in a conventional anti-lock braking function.

The availability of independent actuator control offers other advantages. The force generated by each EMA can be tailored to a given situation. Normally, the EMA's would be driven to apply equal forces to the pressure plate 29. In other situations, such as adverse vibration conditions, they could be driven to apply unequal forces with the distribution tailored to the situation, such as providing damping. This active vibration damping may be accomplished by mounting one, or more, accelerometer(s) 55 in the brake or carrier housing. This vibration sensing means 55 associated with the brake 31 is coupled to the vibration threshold sensing circuit 85 in control unit 61. The control unit operates the brakes in a normal mode 81 so long as the vibration sensed by the sensing means 55 remains below a specified level and changes to a vibration damping mode or corrective routine 87 when the sensed vibration exceeds the specified level. The vibration sensor signals may undergo more sophisticated analysis and the corrective routine be based on that analysis. The corrective routine may be a program of variations in the energization of individual ones of the actuators in accordance with a stored sequence during the braking event to vary the braking force applied to the wheel to avoid excitation of adverse vibration of the brake thereby preventing the build-up of brake vibration induced by the braking force. For example, as the ECU 61 receives and processes the accelerometer signal, it may be programmed to respond to a specific vibration spectrum with a corresponding EMA force distribution spectrum. Thus, in response to a given vibration condition, the active damping mode of force distribution would be initiated by the ECU. It would continue to work through the active damping mode until the vibration conditions met specific criteria for a normal mode. Another approach would be to have the ECU examine the EMA feedback signals for "indications" of adverse vibration conditions and to respond accordingly. For example, the ECU

could "look" for backdriving of the EMAs by the brake stack (at a high level, this could be an indication of whirl) and alter the command signals to compensate. In this case, there would be no need for accelerometers but "feedback loops" would be utilized (the feedback in this example is coming from the EMAs). In another, even simpler approach, the ECU could be programmed to apply the EMA's in a pattern that would avoid exciting adverse vibration conditions. This selective application could be derived empirically (by test), validated and then programmed. In this approach, there would not be any need for accelerometers or feedback loops.

It will be understood that, while only two wheel and brake assemblies have been illustrated in Figure 2, additional wheel and brake assemblies may be connected in parallel with those illustrated to receive like selective energization, or additional wheel and brake assemblies with their own dedicated control circuits may be added allowing independent control of the additional individual actuators. While the invention has been described in conjunction with electromechanical actuators, hydraulic or other actuator schemes may advantageously employ this invention.

In summary, the invention has a number of advantages over known prior braking systems. The system architecture is structured to allow each EMA to act independently under the control of the ECU 61. Any given actuator may be operated at a different force level, and be at a different piston displacement, velocity, or acceleration from the other EMA's in the brake system. This independent EMA control has several potential benefits including enhanced fault accommodation, improved thermal management capability particularly during park or tow operation, and the capacity for vibration damping. There is the additional benefit of improved tolerance to friction material damping characteristics.

Specifically, an ability to compensate for, or to avoid, adverse vibration modes allows friction materials to be designed and manufactured with

less emphasis on vibration performance characteristics. This may have cost benefit implications for friction material design and manufacture.

## WHAT IS CLAIMED IS:

1. A braking system of the type having a plurality of individual  
brake actuators selectively energizable upon a braking command to effect  
the frictional restraint of vehicle wheel rotation, the improvement  
5 comprising control means operable in a first mode to equally or unequally  
energize all of the plurality of actuators associated with the wheel upon  
receipt of a braking command, and operable in a second mode to equally  
or unequally energize less than all of the plurality of actuators associated  
10 with the given wheel upon receipt of a braking command.

2. The improvement of Claim 1, wherein in the second mode and  
upon receipt of a braking command, certain ones of the actuators receive  
equal energization while other of the actuators receive less energization  
that said certain ones of the actuators.

3. The improvement of Claim 1, wherein in the second mode and  
upon receipt of a braking command, certain of the actuators receive equal  
energization while other of the actuators remain un-energized.

4. The improvement of Claim 1, wherein the individually  
energizable actuators are electrically actuated electromechanical  
20 actuators.

5. The improvement of Claim 1, wherein the vehicle wheel  
comprises one of several wheels of an aircraft, the control means  
operating in the first mode during landing and roll-out of the aircraft and in  
the second mode during taxi and towing of the aircraft.

6. The improvement of Claim 1, further comprising vibration  
sensing means associated with the wheel and connected with the control  
means, the control means operating in the first mode so long as vibration  
sensed by the sensing means remains below a specified level and in the  
second mode when the sensed vibration exceeds the specified level.

7. An electrically actuated braking system of the type having a  
brake disk stack selectively compressed to restrain wheel rotation; a  
30

plurality of brake actuators disposed at a carrier housing in an annular pattern about the axis of wheel rotation and selectively energizable upon occurrence of a braking command to apply a braking force to thereby compress the stack and restrain wheel rotation; a first circuit for  
5 energizing only a first proper subset of the plurality of the brake actuators upon occurrence of a braking command; a second circuit for energizing only a second proper subset of the plurality of brake actuators upon occurrence of a braking command; means for monitoring wheel motion and providing a plurality of distinguishable control signals indicative of  
10 different monitored wheel motion conditions; and circuitry for selectively enabling the first circuit and not the second circuit in response to certain of the control signals, the second circuit and not the first circuit in response to other of the control signals, and both the first and second circuits in response to still other of the control signals.

15 8. The electrically actuated braking system of Claim 7, wherein the first and second proper subsets are disjoint.

9. The electrically actuated braking system of Claim 7, wherein the first and second circuits each energize exactly one brake actuator.

20 10. The electrically actuated braking system of Claim 9, further comprising additional circuits, one for each additional brake actuator, whereby enabling of each individual one of the brake actuators is determined by the control signals.

25 11. The electrically actuated braking system of Claim 7, wherein a union of the first and second proper subsets comprises the entire plurality of brake actuators.

30 12. The electrically actuated braking system of Claim 7, wherein the means for monitoring wheel motion includes means responsive to the control signals to select the subsets whereby the particular actuators employed during a braking event are determined, at least in part, by monitored wheel motion.

13. The electrically actuated braking system of Claim 12, wherein the responsive means is active during an entire braking event whereby particular actuators employed during a braking event may be modified during the braking event as determined by the monitored wheel motion.

5 14. The electrically actuated braking system of Claim 7, wherein the plurality of brake actuators are electromechanical actuators.

15. A braking system of the type having a plurality of individual brake actuators selectively energizable during a commanded braking event to effect the frictional restraint of vehicle wheel rotation, a method of  
10 reducing brake vibration comprising:

monitoring brake vibration during a braking event; and  
modifying, in accordance with the monitored vibration, the energization of individual ones of the actuators during the braking event to modify the braking force applied to the wheel and reduce the vibration  
15 of the brake.

16. The braking system of Claim 15, wherein the system is responsive to back driving of the actuators by the brake, in order to modify appropriately the energization of the actuators.

17. A braking system of the type having a plurality of individual  
20 brake actuators selectively energizable during a commanded braking event to effect the frictional restraint of vehicle wheel rotation, a method of reducing the heat generated by actuator energization during relatively slow speed ground operations comprising:

monitoring vehicle speed; and  
25 reducing the energization of the energized brake actuators.

18. A braking system of the type having a plurality of individual brake actuators selectively energizable during a commanded braking event to effect the frictional restraint of vehicle wheel rotation, a method of reducing the heat generated by actuator energization during relatively  
30 slow speed ground operations comprising:

monitoring vehicle speed; and

disabling certain ones of the individual actuators when the monitored speed is below a specified threshold.

19. A multi-wheel vehicle braking system of the type where each wheel has a plurality of individual brake actuators selectively energizable during a commanded braking event to effect the frictional restraint of vehicle wheel rotation, a method of maintaining substantially the same braking force on each wheel during the braking event comprising:

reducing the number of actuators of a given wheel which are energized during a braking event; and  
increasing the level of actuator energization to at least some of the reduced number of actuators thereby avoiding the tendency of another more forcefully braked wheel inducing a sideways force on the vehicle.

20. The method of Claim 19, wherein the same increased level of actuator energization is applied to all of the reduced number of actuators.

21. An electrically actuated braking system of the type having an electronic control unit and a plurality of individual brake actuators selectively energizable during a commanded braking event to effect the frictional restraint of vehicle wheel rotation, a method of avoiding braking induced wheel vibration comprising:

predetermining a sequence of energization levels for individual ones of the actuators to minimize the introduction of wheel vibrations during a braking event;

storing the predetermined sequence in the electronic control unit;  
and

varying the energization of individual ones of the actuators in accordance with the stored sequence during the braking event to vary the braking force applied to the wheel to avoid excitation of adverse vibration of the brake thereby preventing the build-up of brake vibration induced by the braking force.

22. A multi-wheel vehicle braking system of the type where each wheel has a plurality of individual brake actuators selectively energizable



during a commanded braking event to effect the frictional restraint of vehicle wheel rotation, a method of maintaining substantially the same braking force on each wheel during the braking event comprising:

- 5        monitoring each actuator for proper operation during a braking event;
- disabling an actuator upon the occurrence of improper operation thereby reducing the braking force on the associated wheel; and
- disabling another actuator of another wheel to reduce the braking force on the another wheel to substantially the same reduced level as the
- 10    associated wheel.

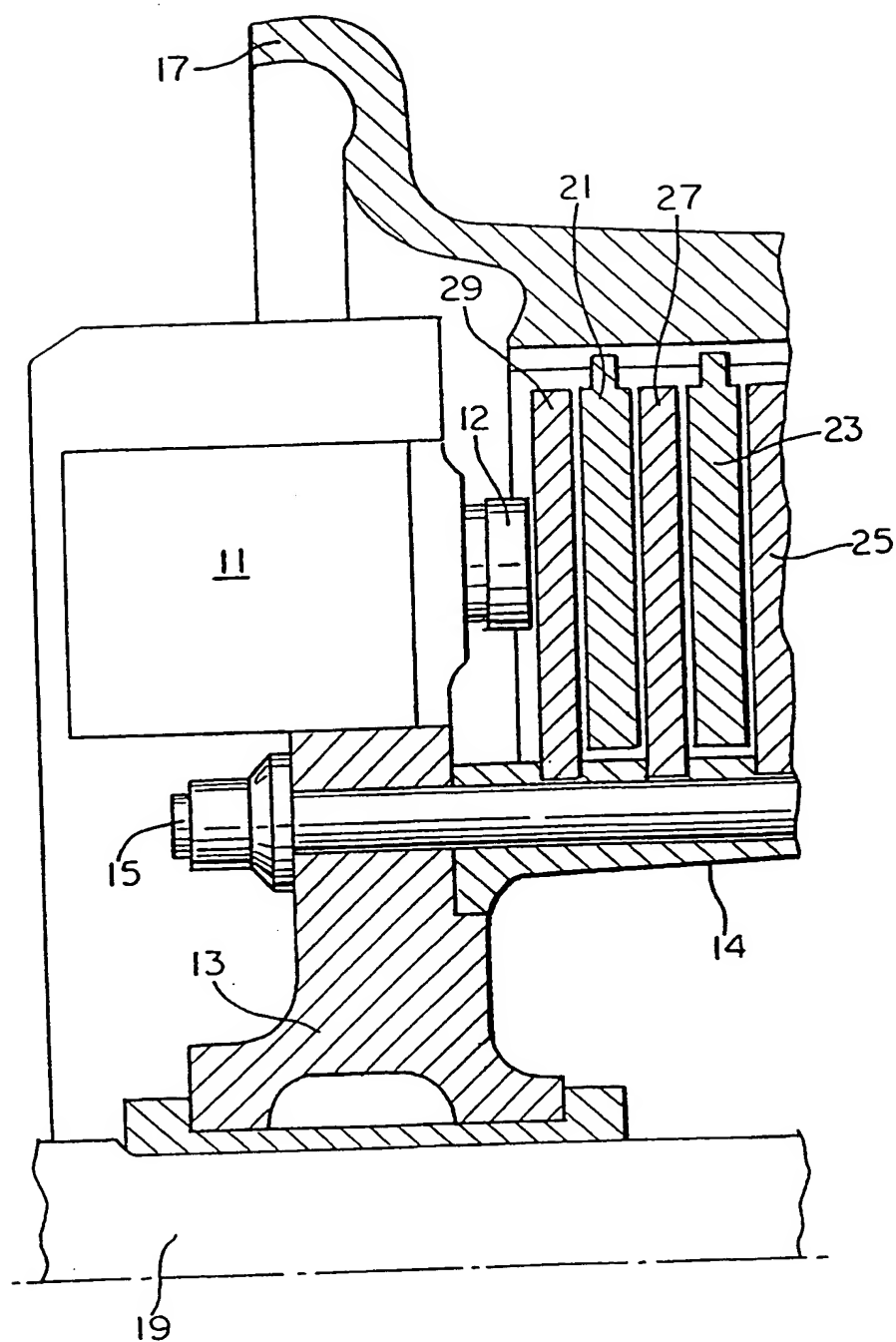


FIG. 1  
(PRIOR ART)

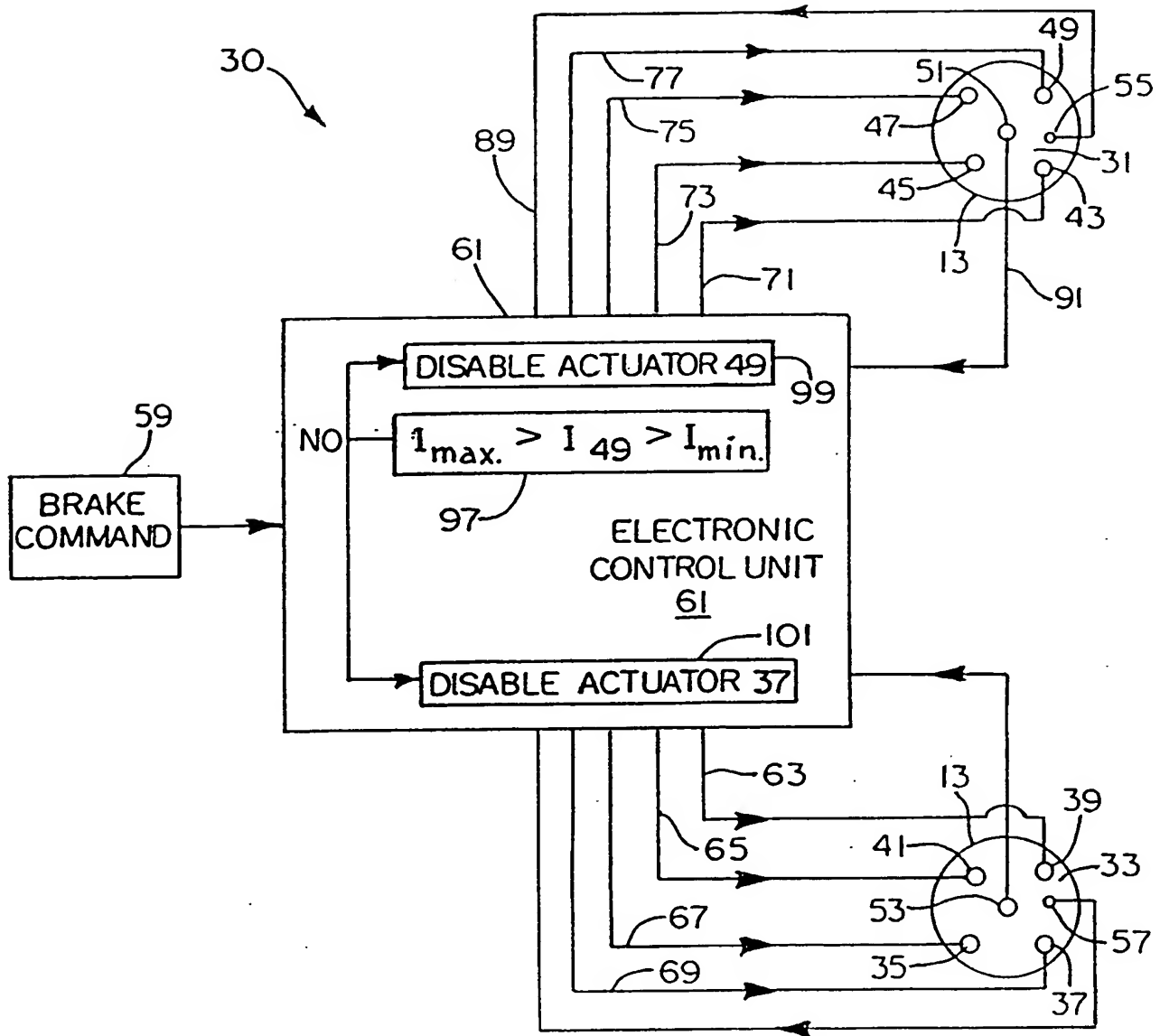


FIG. 2

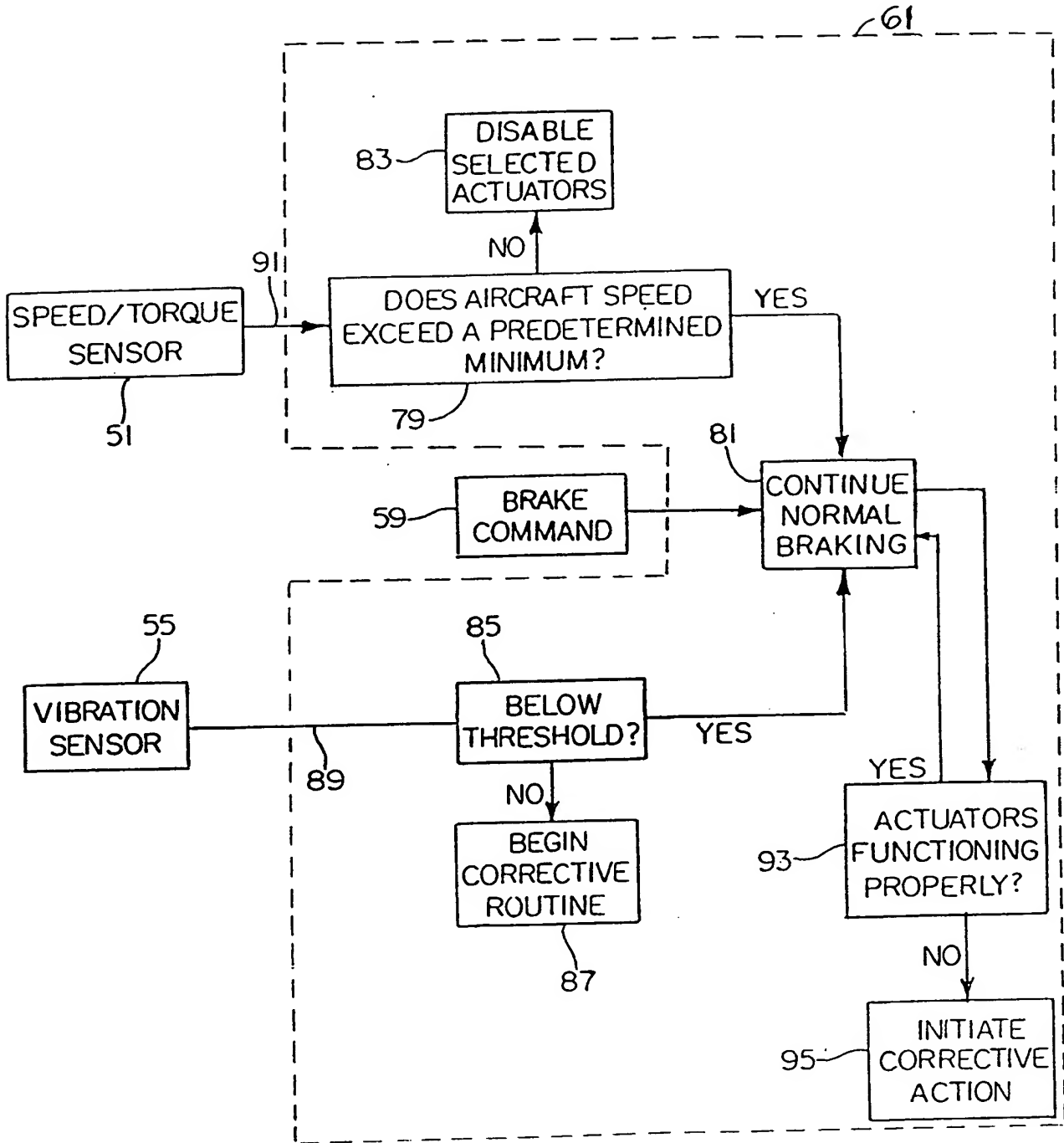


FIG. 3